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SOA-based fiber ring laser with seed of DFB wavelength scanning for relative humidity measurement using an air-guided photonic crystal fiber

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Abstract
We propose a novel ring laser for non-hygroscopic coating relative humidity (RH) fiber sensor by means of infrared absorption spectroscopy. A semiconductor optical amplifier (SOA)-based fiber ring laser is used in this scheme. No tunable optical filter is required for the ring laser scheme as wavelength scanning is introduced in the ring using a distributed feedback (DFB) laser. An air-guided photonic crystal fiber (AGPCF) is included in the ring cavity that acts as a sensing head. The detection of gas humidity inside the air holes of AGPCF is determined by DFB wavelength scanning around 1368.59 nm water vapor absorption peak with SOA as a gain medium in the ring. We have experimentally implemented the wavelength scanning of SOA-based fiber ring laser scheme with an AGPCF sensing head of 5 cm and a small gap between single mode fiber and AGPCF to allow air diffusion in and out of the air holes inside the AGPCF. The sensitivity of the sensor is increased from 2.47 to 10.93 mV/1% RH over the range from 0 to 90% RH when the non-lasing mode (single-pass absorption spectroscopy) of the sensor is changed into the lasing mode (multi-pass absorption spectroscopy).

Keywords: SOA ring laser, wavelength scanning, air-guided photonic bandgap fiber, gas humidity sensing, water vapor absorption

(Some figures may appear in colour only in the online journal)

1. Introduction

Humidity refers to the water vapor content in air or other gases. The measurement of humidity is required in a range of fields, including weather forecasting, agricultural activity, semiconductor manufacturing and structural health monitoring. Optical humidity fiber sensors, by comparison to their conventional electronic counterparts, offer specific advantages such as small size and low weight, immunity to electromagnetic interference and the potential for remote operation with multiple sensors. Most fiber sensors work on the basis of hygroscopic coating material coated over the optical fiber for humidity sensing [1–5]. On the other hand, there are non-hygroscopic coating humidity fiber sensors that are based on a direct spectroscopic technique using open path and gas cell where the humidity sensing is related to the light attenuation caused by the water vapor absorption peak at certain wavelengths [6–12]. These humidity sensors are able to measure a wide range of relative humidity (RH) variations but have minimum sensitivity as the light passing through the sensing area is in single-pass only. The implementation of a ring laser for gas detection using erbium-doped fiber amplifier (EDFA) as a gain medium can effectively transform a single-pass short gas cell into a highly efficient multi-pass system

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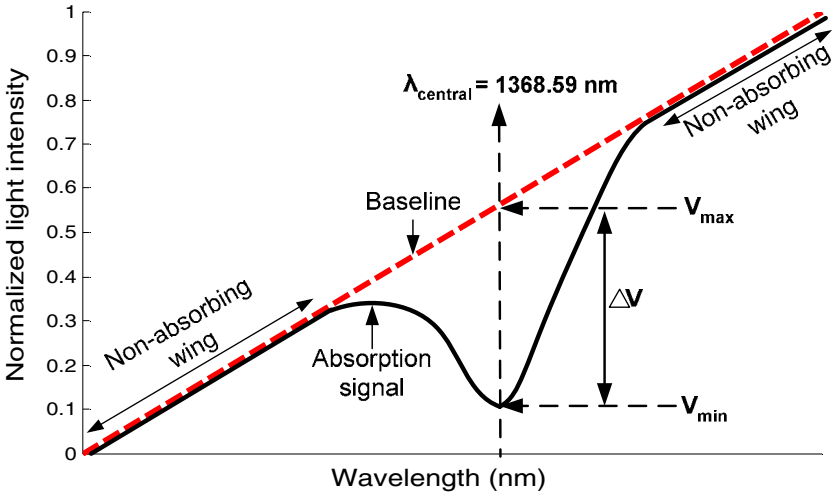

Figure 1. Illustration of the absorption signal in one scanning period that covers the water vapor absorption peak at 1368.59 nm. The zero absorption baseline is also depicted here.

thus improving the sensitivity [13, 14]. However, the EDFA-based ring laser can only be used to detect gas species like methane and acetylene but not the gas humidity as the laser wavelength of the EDFA does not cover the line absorption of the water vapor band. A multi-wavelength fiber-based ring laser on semiconductor optical amplifier (SOA) is also adopted but for C and L band application only [15, 16]. In contrast, the strong absorption lines of water vapor in the near infrared region lie in the O band. Recently, air-guided fibers have generated much interest in exploiting such fibers for sensing and spectroscopic analysis of gases [17, 18]. The air-guided fiber based on ring laser scheme has been adapted for acetylene sensing [19]. Mostly the ring laser schemes reported above used a gas cell or holey fiber as a sensing element and restricted to gas sensing for methane and acetylene only.

In this paper, we present a novel ring laser for non-hygroscopic coating fiber humidity sensor based on a spectroscopic technique. An SOA is used as a gain medium in the ring. Wavelength scanning is introduced into the ring using a distributed feedback (DFB) laser and an air-guided photonic crystal fiber (AGPCF) is included in the ring cavity that acts as a sensing element. The ring laser operates around water vapor absorption peak at 1368.59 nm, which is equal to injected wavelength scanning of the DFB laser to the ring. The humidity detection is realized by analyzing the absorption signal of the ring output which is based on light attenuation at the water vapor absorption peak. The laser emitting at 1369 nm band is chosen to measure RH because of the strong absorption of water vapor and takes advantage of the mature telecommunication technology at this near infrared band. One end of the HC-PBF is sealed shut by splicing it to the standard single mode fiber (SMF) pigtail of the DFB laser. A small gap is introduced between the other end of AGPCF and SMF to allow air diffusion for the AGPCF. To the best of our knowledge such a ring laser humidity fiber sensor scheme is reported for the first time. It is also the first ring laser that has an operation wavelength at the peak of water vapor absorption in the near infrared region that lies in the O band reported so far. This fiber sensor scheme has wide range humidity detection with high sensitivity when operating in the lasing mode, and hence can find applications in many areas that require high sensitivity gas humidity measurements.

2. Working principle

The humidity sensing for the fiber sensor in this work depends on the water vapor content in the air inside the AGPCF. The presence of water vapor is then determined according to the Beer–Lambert law [20]. The ring laser output power will decrease when humidity is increased due to the light attenuation caused by light absorption at the water vapor absorption band. By using a DFB wavelength scanning scheme, a narrow line-width of the DFB is tuned around the targeted water vapor absorption peak. ΔV is the voltage change that shows the change of absorption caused by a certain humidity level with regard to dry air (0%RH, corresponding to the baseline, $\Delta V = 0$) and is defined as

$$\Delta V = V_{\max}\left(\lambda_{\text{central},}0\%\text{RH}\right) - V_{\min}\left(\lambda_{\text{central},}x\%\text{RH}\right), \quad (1)$$

where $V_{\max}$ is a voltage at a central wavelength of water vapor absorption when the humidity level is equal to 0%RH. $V_{\min}$ is a voltage at a central wavelength of water vapor absorption at a certain n%RH ($x = 0$–100). The baseline can be constructed by linear line fitting over the non-absorbing wavelengths in both wings of the absorption signal as shown in figure 1. By using the baseline as a reference, RH level can be determined accurately. This is because ΔV is dependent only on absorption of water vapor associated with a certain RH. Hence ΔV is immune from other physical factors such as noise of laser source, fiber loss and unwanted attenuation in the probed region.

In the past, generally an open path probe region was used to sense gas species but currently with the advent of optical fiber technology, the AGPCF has slowly replaced the traditional bulky gas cell. The length of the sensing region using either open path or AGPCF does influence the sensitivity of the sensor. A longer sensing region will increase the sensitivity of the sensor. For open path probe sensing, there is a

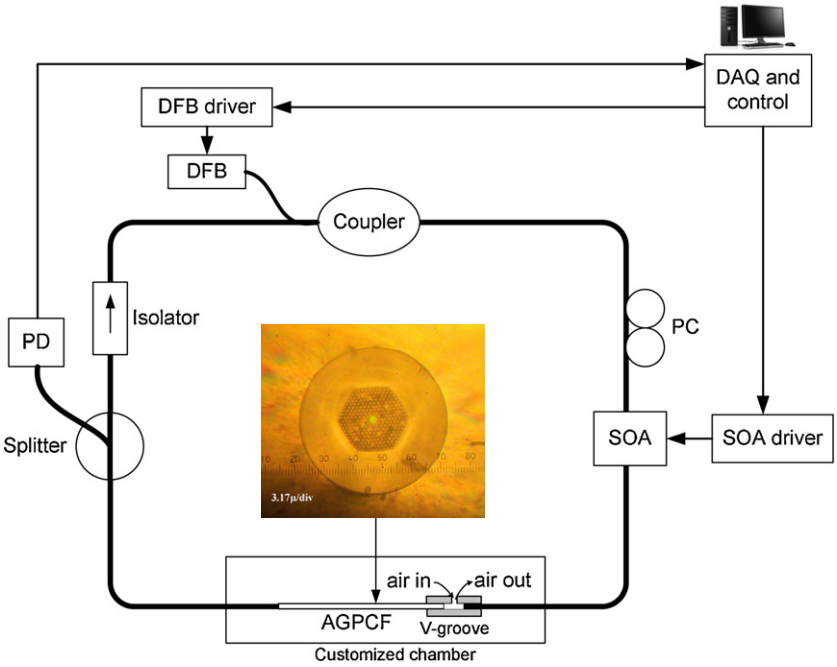

Figure 2. Experimental setup for humidity detection and AGPCF (sensor head) cross section.

limitation in terms of the length that can be applied. When the length of the open path is increased, the sensitivity will increase but the loss is also increased due to light loss that passes through the open air thus decreasing the signal-to-noise ratio (SNR). The length of the open path can be increased without significantly reducing the SNR by using a white cell [20] but it will compromise the bulkiness of the sensing region. On the other hand, the AGPCF is able to provide a long interaction with a low loss (by increasing the length of the AGPCF) between light and gas due to the low light propagation loss of the AGPCF and hence increase the sensitivity of the sensor with a good SNR. The demonstration of the AGPCF as a gas cell can lead to an all-fiber gas cell, which can make it easier to integrate with optical network and increase the flexibility to install the sensor in small and hard-to-reach spaces. However the main disadvantage of a sensor based on the AGPCF is the limitation of gas diffusion hole, which only depends on a small gap between the AGPCF and the SMF. As a result, it takes a long time for gas to get in and out of the longer AGPCF thus increasing the sensor response time. This issue can be overcome by making small dimension holes along the AGPCF using a femtosecond laser [21] or any other means [22] that can be realized to decrease the response time of such sensor to an order of milliseconds.

3. Experiment

The experimental setup of the SOA-based fiber ring laser with DFB wavelength scanning for gas humidity detection is shown in figure 2. The configuration consists of the SOA (BOA1036S Covega Thorlab), a coupler, a polarization controller (PC), a DFB laser source, AGPCF cell, a splitter, an isolator and a photodetector (PD). The SOA is used as the gain medium in a ring cavity. This SOA has an optical 3 dB bandwidth of ∼80 nm, central wavelength at 1353 nm and saturated power output of 14 dBm. The DFB laser source at 1368 nm band is coupled into the main cavity by a 50:50 coupler. The isolator is used to ensure unidirectional operation and a splitter with the chosen coupling ratio of 90:10 allows for strong optical feedback (90% of the power) into the ring cavity. The PC is used to control the states of polarization in the ring cavity. The output signal of the ring is monitored by a PD. The SOA and DFB have their own laser driver and are controlled by the DAQ card. In order to use DFB wavelength scanning to detect gas humidity in the ring laser configuration, the scanning range must cover the line absorption of water vapor and the DFB laser source should have a line-width significantly smaller than the absorption line of water vapor [23]. The wavelength amplification of the SOA in the ring cavity must also work in the range of wavelength scanning of the DFB laser. Figure 3 shows that the line absorption of water vapor at 1368.59 nm is in the range of DFB wavelength scanning with drive voltage from 100 to 450 mV. When the drive voltage of the DFB laser is increased, the output power and wavelength of the DFB laser are also increased. Saw-tooth modulation with amplitude from 100 to 450 mV and frequency of 100 Hz is applied to the DFB laser driver to realize this scanning technique. The total range of wavelength scanning is ∼2 nm. The output wavelength of the DFB is at the position of line absorption of water vapor when the DFB drive voltage is around 300 mV. There are number of water vapor absorption bands which are listed in the HITRAN database. The absorption bands are centered around 930, 1120, 1370 and 2600 nm. Although the strongest absorption is in a band near 2600 nm, there are more convenient laser sources at shorter wavelengths. In this paper, the 1368.59 nm water vapor absorption feature is used to measure the absorption of gas humidity which arises from the $2_{12} \leftarrow 3_{13}$ rotational line within v_3+v_2 vibrational band. This is because the 1368.59 nm absorption feature has one of the highest line strength values at 1.8×10^{-20} cm/molecule

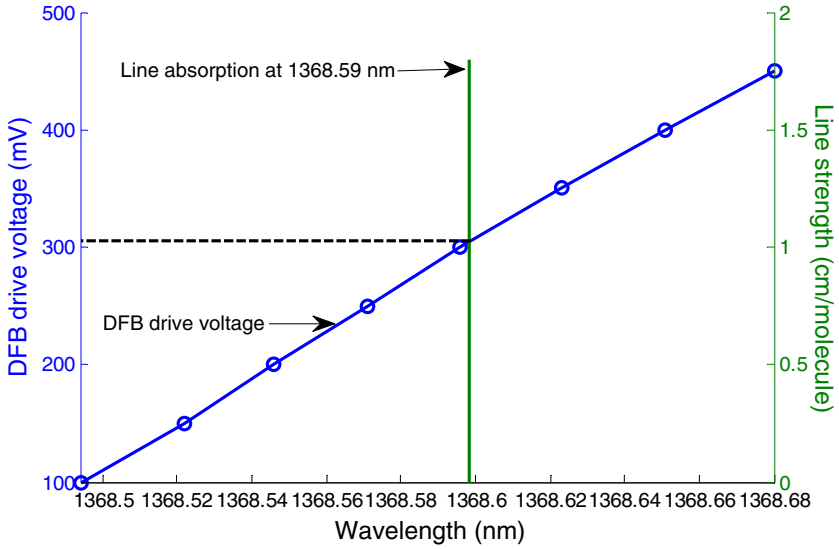

Figure 3. DFB wavelength scanning range and line absorption of water vapor at 1368.59 nm.

in the near infrared region that lies in 1370 band [24]. In addition, it includes only one transition so that there will be no chance for that transition to overlap with neighboring transitions when the pressure broadens [25], which can cause complicated absorption measurement. This transition is also free of interference from the presence of other gas molecules in normal open atmosphere such as nitrogen, carbon dioxide and oxygen based on the extracted HITRAN 2008 molecule database [24].

With the AGPCF cell placed within the ring cavity, very large number of passes through the AGPCF cell can effectively transform a short AGPCF cell into a highly efficient multi-pass system and therefore improves the sensitivity. AGPCF is chosen as the sensing element due to over 98% of the light propagating in the holey region of the AGPCF [26]. The AGPCF consists of eight rings of air holes arranged in hexagonal pattern and one hollow core as depicted in figure 2 and guides light by a photonic bandgap effect. The cladding diameter and hollow core are around 50 and 10 μm, respectively. One end of AGPCF is spliced to a single mode optical fiber (SMF-28) using a fusion splicing machine with splice loss around 1 dB. A splice program in the splicing machine with optimized parameters was used in the splicing process to ensure repeatability of the splicing process with a low splice loss. On the other end, a small gap was adjusted to $\sim$50 μm [25] for efficient filling while keeping good signal coupling efficiency using 3D stages and fixed to the V-groove fiber holder. This gap is open to ambient atmosphere and acts as an air diffusion hole for the sensor head of AGPCF. The length of the AGPCF used in this experiment is $\sim$5 cm.

The humidity response of the sensor is studied at ambient pressure by placing it in a customized chamber. The humidity in the chamber is varied by pumping wet air and dry nitrogen gas in a controlled manner. An electronic RH sensor with an accuracy of 4% RH was used to monitor the humidity and temperature inside the chamber for calibration.

4. Results

The SOA ring laser based operation is dependent on the gain of SOA. Figure 4 shows the peak power of DFB wavelength scanning of SOA ring laser against different gain of SOA when the DFB drive voltage is fixed to 100 mV. From the figure, the SOA fiber ring laser with DFB laser source achieves lasing when the SOA gain reaches 88 mA with DFB drive voltage fixed to 100 mV. At the lowest gain of 50 mA, there is insufficient gain for the SOA to reach the lasing mode. As the gain is increased, the SOA is able to provide more sufficient gain and thus achieve a lasing mode around 88 mA. The peak power of the ring then starts to saturate around -20 dBm although the gain of the SOA keeps increasing till 150 mA. The threshold for this ring to start lasing is 88 mA. The absorption signals of the SOA-based ring laser are shown in figure 4. A zero absorption baseline is realized based on the DFB saw-tooth modulated signal in which a linear fit to the non-absorbing wings of the absorption feature is used to extrapolate the reference signal. The linear fit can be either one or both sides of non-absorbing wings of the absorption feature. The non-lasing and lasing modes of the ring are compared in figure 5. In non-lasing mode, the absorption signal is caused by humidity level at 85% RH while the absorption signal in lasing mode is at 35% RH with the same temperature condition at 25 °C. It is observed that the absorption signal of the lasing mode far exceeded the absorption signal in non-lasing mode, although the humidity level tested for the lasing mode (35%RH) is much lower than the humidity level tested in non-lasing mode (85% RH). This is because for non-lasing mode, the light that passes through the AGPCF cell is in single-pass only but when the AGPCF cell is placed within the ring cavity in lasing mode, the very large number of passes through the cell transforms the short cell into a highly multi-pass system which greatly improves the sensitivity. The gain of the SOA in the ring laser for the lasing and non-lasing modes is set to 150 and 70 mA, respectively. Figure 5 also shows that the center of

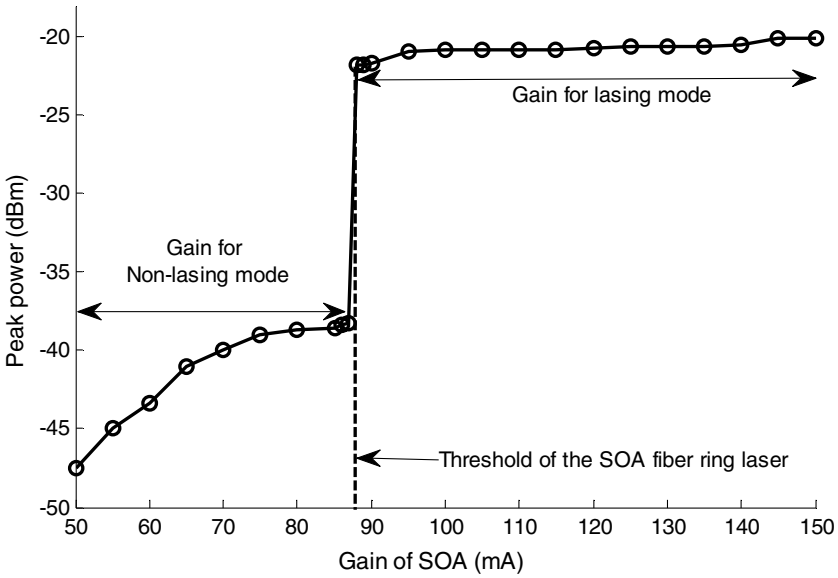

Figure 4. Peak power of the ring output against the gain of the SOA with DFB drive voltage fixed at 100 mV.

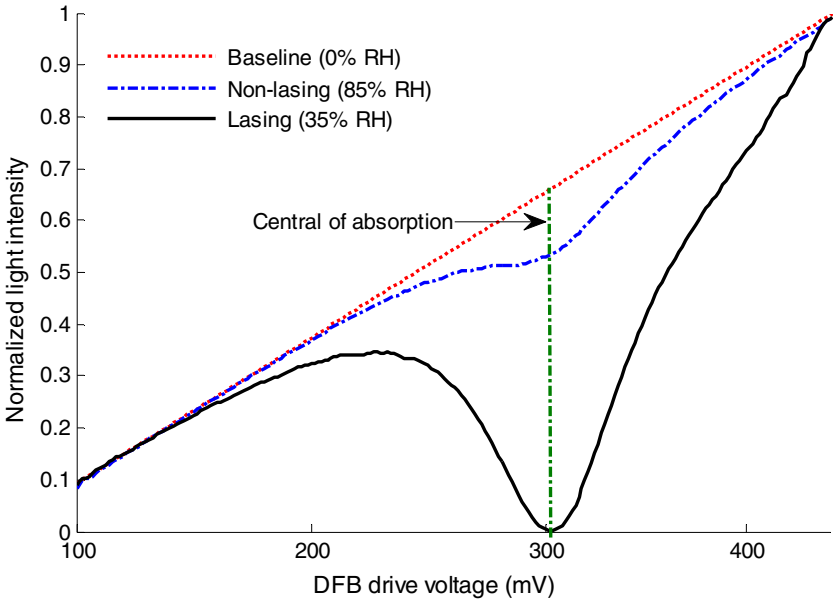

Figure 5. Comparison of absorption signals in one scanning period for non-lasing mode at 85% RH and lasing mode at 35% RH. Baseline is used as a reference for 0% RH.

the absorption region is around 300 mV of DFB drive voltage, which is equivalent to the line absorption of water vapor at 1368.59 nm as shown in figure 3.

The sensitivity of the lasing and non-lasing mode of the system is then compared by plotting the ΔV versus RH in figure 6. The ΔV changes linearly with the RH and the sensitivities of the lasing and non-lasing modes are 10.93 and 2.47 mV/1% RH, respectively. It is proved that the sensitivity of the lasing mode is much higher than the non-lasing mode. The ΔV for 35% RH in lasing mode is much higher than the ΔV for 85% RH in non-lasing mode because of the higher absorption occurring in lasing mode as shown in figure 5. When compared to our previous fiber humidity sensor which is based on the same length of AGPCF [27], the sensitivity of the SOA ring laser sensor shows a much higher sensitivity at 10.93 mV/1%RH while the sensor in our previous work only shows a sensitivity of 3.02 mV/1%RH. However, that comparison is not an exact evaluation due to possibilities of different gain and loss of both sensor systems. By referring to the non-lasing mode sensitivity of the ring laser sensor, a direct comparison can be made due to non-lasing mode which is equal to the single-pass absorption operation with a similar scanning scheme in our previous sensor which shows a sensitivity of 2.47 mV/1%RH. It is proved that the sensitivity of the ring laser sensor is much higher than the sensor used in our previous work. This is because the light that passes through the AGPCF cell is in single-pass only for our previous sensor, but when the AGPCF cell is placed within the ring laser cavity,

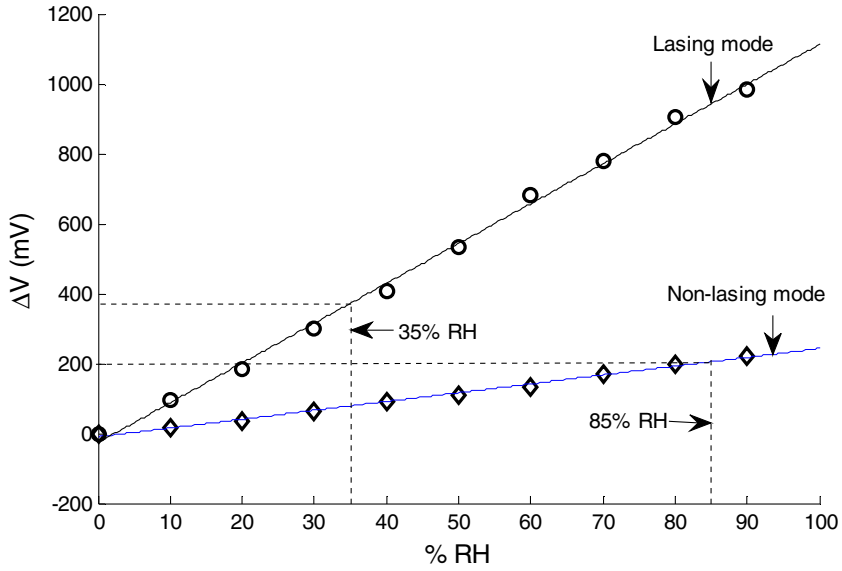

Figure 6. ΔV versus relative humidity (RH) for lasing and non-lasing modes of the system.

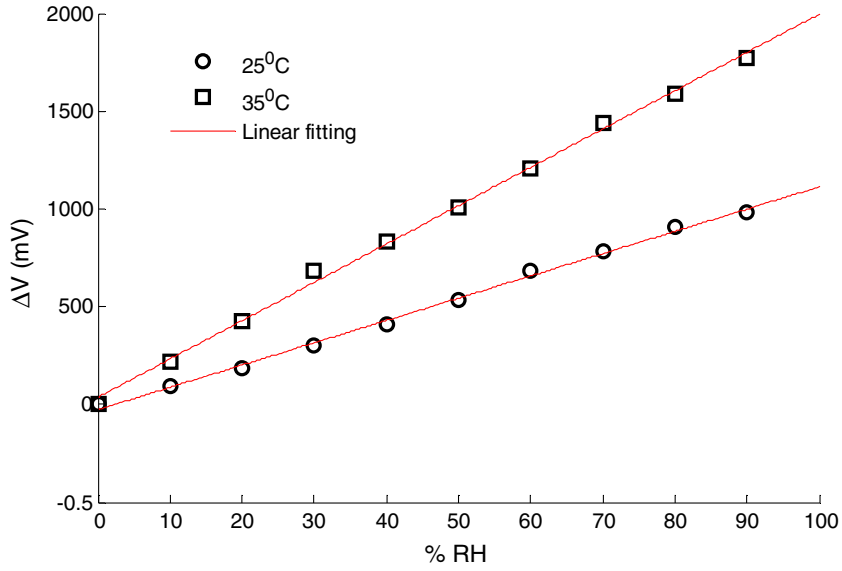

Figure 7. Temperature effect of the RH measurement for the sensor.

the very large number of passes through the cell transforms the short cell into a highly multi-pass system thus significantly improving the sensitivity. The voltage difference (ΔV) versus RH is also shown in figure 7 for difference in temperature condition. The sensor detection range is tested from 0 to 90% RH. It was found that the curve slope of the temperature at 25 °C is 10.93 mV/1% RH, and much higher sensitivity of 19.67 mV/1% RH is obtained when the temperature condition is increased to 35 °C. RH is defined as the ratio of partial pressure of water vapor to saturable water vapor pressure at a certain temperature. The saturable water vapor pressure in air is a function of temperature. Higher temperature means higher saturable water vapor pressure indicating that the air is able to hold more water vapor. Hence at certain RH, higher temperature means higher water content, higher water vapor absorption and eventually higher signal magnitude which is proportional to water vapor absorption. Therefore, this sensor is almost independent of the temperature conditions. Figure 8 shows the relationship between RH with water vapor in parts per million by volume (ppm) using a commercial software tool called VAISALA humidity calculator. It is shown that volume of water vapor is increased from low to high temperature at certain RH. This ring laser humidity sensor has high sensitivity from low to high humidity detection region (0 to 90% RH), whereas the non-hygroscopic coating humidity sensor based on the effective refractive index (RI) change of the guided modes using a photonic crystal fiber interferometer [28] has the disadvantage that sensitivity is not fine enough for the small diversification of the effective RI in low RH and an expensive interrogation unit such as an optical spectrum analyzer (OSA) is required. Furthermore, when compared to work done by other researchers [6, 12], their sensors cover a wide range of humidity detection but the sensor head is in open path which requires a troublesome alignment. On the other

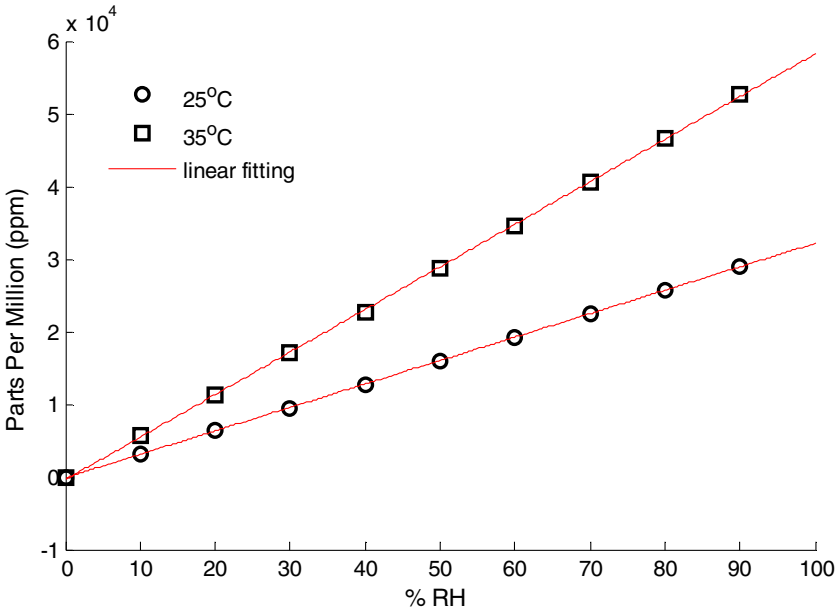

Figure 8. Relationship between relative humidity (%RH) and volume of water vapor in parts per million (ppm).

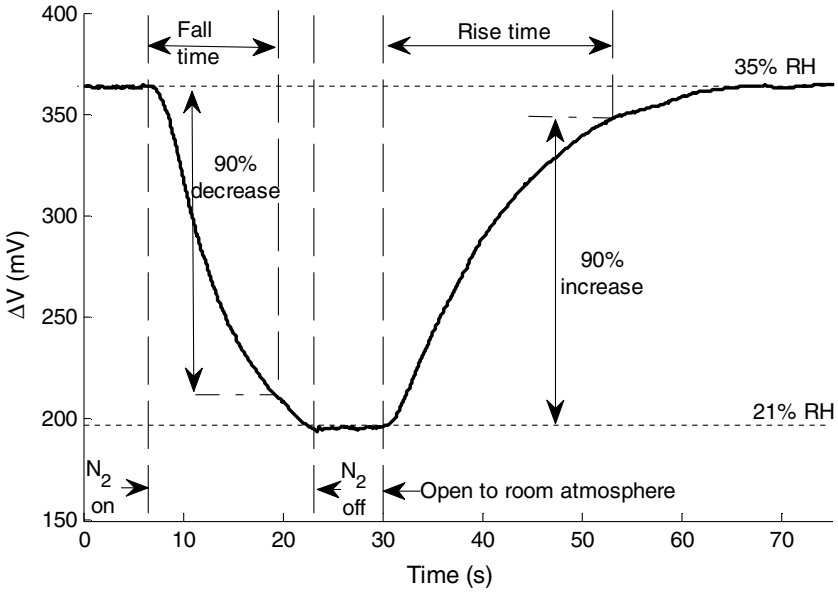

Figure 9. Response time of the sensor with 14% RH change.

hand, we used an air-guided fiber as the sensor head instead of open path to ease the sensor integration in the optical network and eliminate the laser beam alignment. Moreover, the light that passes through the sensing area of their sensor is in single-pass only while our sensor is in multiple pass as the ring laser configuration is applied in our sensor scheme, significantly contributing to high sensitivity detection.

In order to estimate the response time, the proposed sensor is placed in the customized chamber and subjected to a rapid change of RH in lasing mode as depicted in figure 9. The sealed chamber was initially at room humidity of 35% RH. Then the chamber is flushed by dry nitrogen gas for 17 s and sealed again afterwards. The fall time for the sensor to decrease 90% of the ΔV between the steady states of 35% RH and 21% RH was found to be ~13 s. After the sealed chamber reaches a final state of 21% RH, the chamber is opened to room atmosphere. It takes about ~23 s to rise to 90% of the difference between the 21% RH and 35% RH states. The rise time is considered as intrinsic corresponding to the response time of the sensor because it is dependent mainly on the sensor's own response to the RH change while the fall time is considered as extrinsic as it is determined by the rate and duration of the flushing nitrogen gas flow, which are external factors and thus not usually used as the response time of the sensor.

In addition, to estimate the minimum detection of the sensor, a measurement of fixed humidity level at 40% RH was performed for over 30 min inside the chamber as shown in figure 10. The standard deviations of the system in lasing mode and non-lasing mode are calculated. The standard deviations (σ) or noise of the sensor in lasing mode and non-lasing

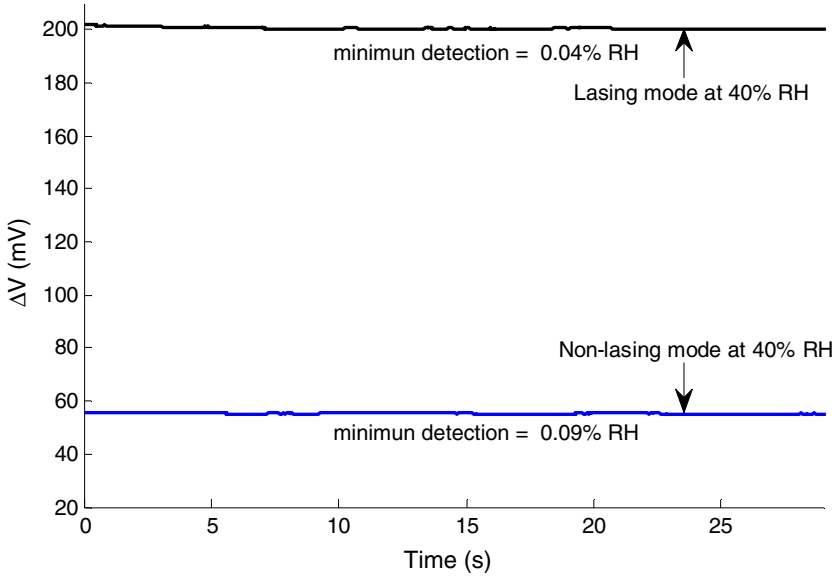

Figure 10. Stability of the sensor for 30 min at fixed humidity level around 40% RH.

mode were found to be 0.42 and 0.22 mV, respectively. Then, the minimum detection of the system can be determined by dividing the standard deviation by the sensitivity of the sensor. The sensor in lasing mode has a lower minimum detection of 0.04% RH when compared to a minimum detection of non-lasing mode which is 0.09% RH. This shows that the lasing mode has a lower minimum detection compared to the non-lasing mode of the sensor although the noise (σ) of the sensor in lasing mode is higher than the noise for the sensor in non-lasing mode. The sensor can be optimized by increasing the length of the fiber and fabricating small holes along the AGPCF in order to increase the sensitivity of the sensor and decrease the response time of the sensor [25, 29].

5. Conclusion

We have demonstrated a novel ring laser with DFB wavelength scanning for non-hygroscopic coating fiber humidity sensor. An AGPCF in the SOA ring cavity is used as the sensor head, which is based on an absorption spectroscopic technique. SOA is used as a gain medium for the ring laser that has a wavelength operation around the water vapor absorption band. By applying DFB wavelength scanning no optical filter is required in the ring cavity as the DFB laser source has a narrow line-width and high peak power. The voltage difference (ΔV) between zero absorption baseline and absorption signal at the peak of the water vapor absorption around 1368.59 nm is used to determine RH level. With the AGPCF sensing element in the SOA ring laser cavity, this sensor scheme demonstrates high sensitivity performance due to a very large amount of light passing through the AGPCF cell that transforms the cell into a multi-pass system in lasing mode. Moreover, the high overlaps between the light and humid air inside the sensing element of AGPCF further increase the sensitivity of the sensor. A 5 cm AGPCF with a small gap as an air diffusion hole shows high humidity sensitivity up to 10.93 mV/1% RH when operating in lasing mode from 0 to 90% RH with good linearity without requiring any external hygroscopic coating on the fiber sensor head. This sensor can find applications in civil engineering where a high sensitivity humidity sensor is needed in low humidity environments.

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